GEOPHYSICAL SURVEY FOR CHARACTERIZING THE HYDRO- GEOLOGIC REGIME OF THE PUU ANAHULU AREA OF NORTH KONA, ISLAND OF HAWAII

GEOPHYSICAL SURVEY FOR CHARACTERIZING THE HYDROGEOLOGIC REGIME OF THE PUU ANAHULU AREA OF NORTH KONA ISLAND OF HAWAII

Prepared For:

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(BGI Project #91052)

December 3, 1991

Table of Contents

1.0 INTRODUCTION

This report contains the results of time domain electromagnetic (TDEM) geophysical surveys for ground water resource evaluation of the Puu Anahulu area of North Kona on the Island of Hawaii. The survey was performed by Blackhawk Geosciences, Inc. (BGI) for the Division of Water Resource Management, State of Hawaii, from October 29 to November 3, 1991.

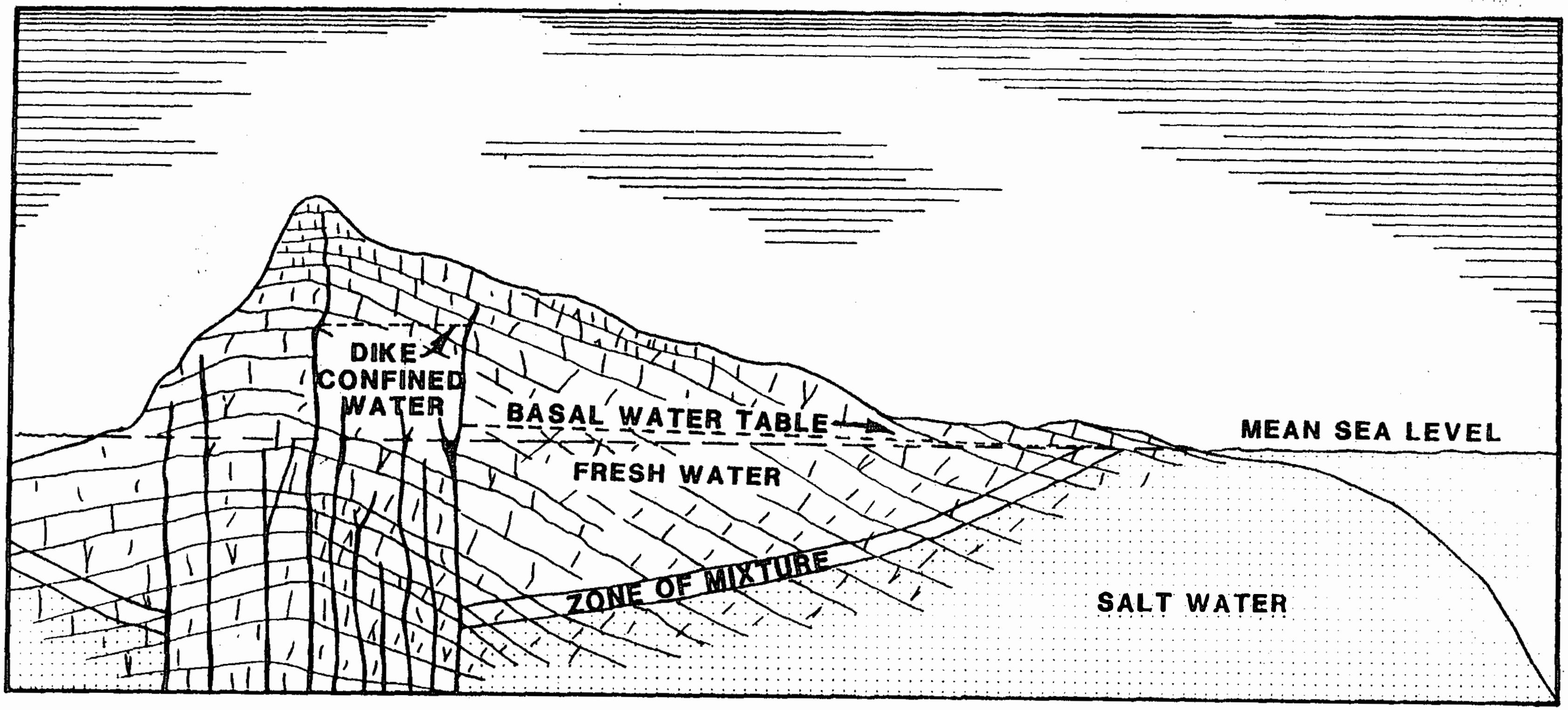
The main objective of the geophysical survey was to characterize the hydrologic regime near Puu Anahulu. The concept for using geophysical surveys for ground water evaluations can be understood using the generalized hydrogeologic cross section shown in Figure 1-1. In the Hawaiian islands, the volcanic rocks are generally highly permeable and rain water rapidly percolates into the ground and migrates downward to the water table. Fresh ground water in island settings is generally found in two environments:

1. Dike-confined waters. Intrusive dikes originating from a magma source below can form ground water dams, and behind these natural dams significant quantities of ground water can be stored.

2. Basal fresh water. The high permeability of the volcanic rocks allows sea water to enter freely under the island, and a delicate balance is reached where a lens of fresh water floats on sea water. In cases where hydrostatic equilibrium exists, the Ghyben-Herzberg relation states that for every foot of fresh water head above sea level there will be 40 ft of fresh water below sea level.

The basal mode water resource was the main focus in the investigations for the State of Hawaii.

Because the electrical resistivity of rock formations is highly dependent upon the salinity of ground water, electrical surface geophysical techniques can map the depth to salt water, and the thickness of the fresh water lens can then be estimated using the Ghyben-Herzberg principle. The impetus for using geophysics is that the cost of a geophysical sounding is about one-thousandth the cost of completing a well at elevations above 1,000 ft. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths. The specific geophysical method employed was time domain electromagnetic (TDEM) soundings. This method was selected because it has proven effective in prior surveys in similar settings in Hawaii.



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SCHEMATIC HYDRO-GEOLOGIC
CROSS SECTION

DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054 FIGURE 1-1

2.0 LOGISTICS AND DATA ACQUISITION PROCEDURES

The TDEM survey was performed by a three man crew consisting of two BGI geophysicists and one local field helper. The locations of the sounding sites were determined during consultation with State personnel and their consulting hydrologist. Due to the remoteness of the project area, no jeep roads or trails were available for access. Therefore, helicopter support was supplied by the Client for the duration of the field survey. At the start of the survey a base control point (BCP) was established on the east corner of sounding 1. The BCP was surveyed in by compass and hip-chain on bearing with the road west of Puu Hinai, and to the north edge of the Kaniku lava flow. The survey line numbers and loop locations are shown on Figure 2-1.

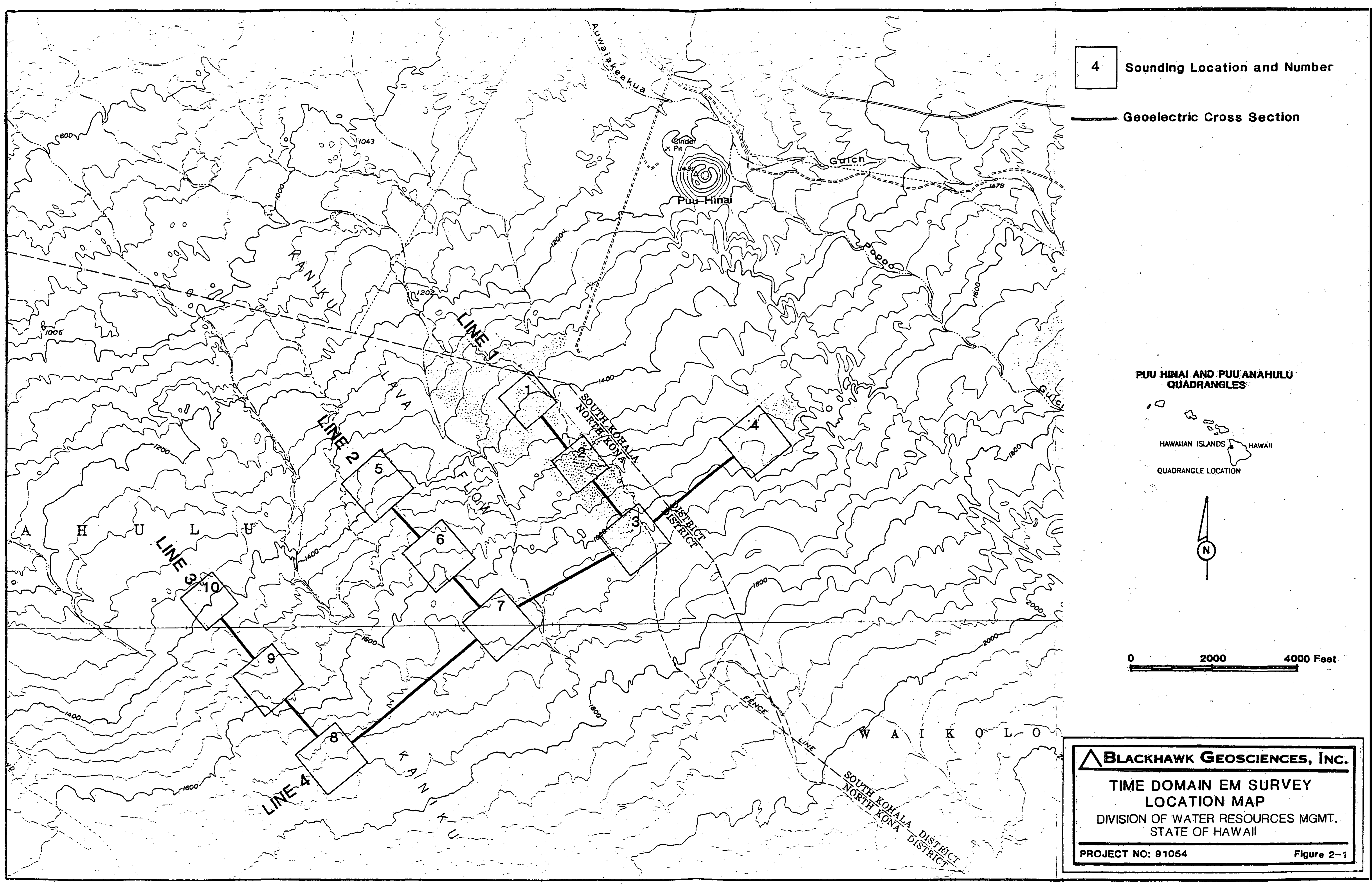
During the five days of field work, a total of 10 sounding measurements were acquired over the area of interest. As the survey progressed the location and number of soundings changed at the request of the consulting hydrologist, to include only measurements between approximately the 1,400 ft and 1,700 ft elevation level. From the BCP, bearings of $N40^0W$ and $S50^0W$ were used throughout the survey area to layout transmitter loops and when measuring from loop-to-loop and from line-to-line. Elevations of sounding centers were measured with a handheld barometric altimeter in the field and checked periodically against the helicopter altimeter during each day to maintain reliable ($\pm$ 20 ft) elevation readings. A daily log of field activities during the survey is given in Table 2-1. Transmitter loop sizes varied from 1,000 ft by 1,000 ft to 1,200 ft by 1,200 ft in the study area according to depth of investigation needed and the logistics of accomplishing the sounding measurement.

2.1 PROCEDURES

The Geonics EM-37 TDEM system was utilized on this survey. The system basically consists of a transmitter and a receiver. The transmitter loop is constructed of 10 to 12 gauge insulated copper wire. The wire is laid on the ground surface in a square loop varying in size, depending upon the required depth of investigation (larger loop sizes for deeper measurement). A transmitter and motor generator are connected into the non-grounded loop at one corner. A time-varying current is pulsed through the wire at two different base frequencies. The TDEM receiver measures and records the decay of the vertical magnetic field through a receiver coil placed at the center of the non-grounded transmitter loop. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were utilized at base frequencies of 3 Hz and 30 Hz. During data acquisition numerous transient decays are collected with the receiver for each sounding. Readings were acquired at several receiver gains with opposite receiver polarities for each sounding location. The readings were stored in a DAS-54 solid state data logger, and were nightly transferred to a personal computer for processing. A technical note is given in Appendix A which describes and illustrates the principles of TDEM.

Table 2-1. Daily log of field activities

Date (1991)	Activity
October 27	Demobilize from other Pacific jobs to Kailua-Kona, HI in conjunction with other surveys.
October 28	One-half day of mobilization, clear equipment through customs.
October 29	Perform reconnaissance of sounding site 1, and establish base control point (BCP) on east corner. Transport TDEM equipment and crew by helicopter to east corner of sounding 1. Acquire measurement of soundings 1 and 2.
October 30	Measurement of soundings 3 and 4.
October 31	Measurement of soundings 5 and 6.
November 2	Measurement of soundings 7 and 8.
November 3	Measurement of soundings 9 and 10.
November 4-5	Demobilization of equipment and BGI personnel from Kailua-Kona, HI to Golden, CO.
	(October 28 and November 1 are work at other Hawaii locations)



BLACKHAWK GEOSCIENCES, INC.

TIME DOMAIN EM SURVEY LOCATION MAP

DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054

Figure 2-1

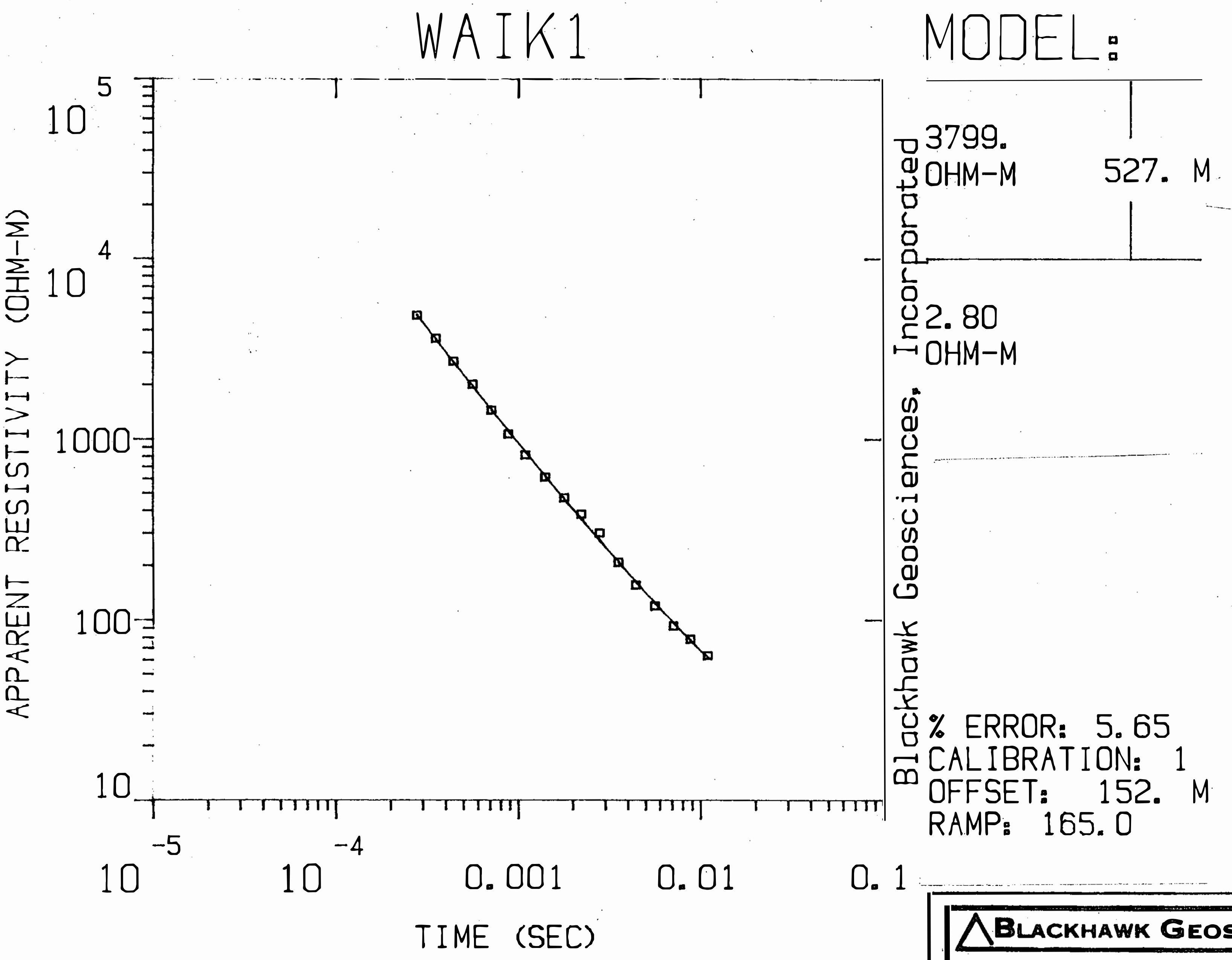
3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a personal computer. The data for each sounding location is edited and combined (both 3 Hz and 30 Hz frequencies) to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

An example data set is given in Figures 3-1 and 3-2 for sounding WAIK1 (sounding number 1). Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed behavior of the true resistivity layering shown on the right. Thus, the section is interpreted to consist of two layers, - the first layer has a thickness of 527 m (1,729 ft) with a resistivity of 3,799 ohm-m, and the resistivity of the second layer is 2.8 ohm-m. Figure 3-2 lists model and survey parameters, and in column 4 the error between measured and computed data in each time gate.

The apparent resistivity curves and data sheets for all soundings are contained in Appendix B.



BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET
SOUNDING WAIK1
DIVISION OF WATER RESOURCE MGMT.
STATE OF HAWAII

PROJECTNO: 91054 **Figure 3-1**

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		426.7	1400.0		
3799.13	527.1	-100.3	-329.2	0.1	0.1
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.80E-04	4.83E+03	4.86E+03	-0.654	
2	3.55E-04	3.60E+03	3.56E+03	1.050	
3	4.43E-04	2.69E+03	2.67E+03	0.837	
4	5.64E-04	2.00E+03	1.96E+03	2.250	
5	7.13E-04	1.44E+03	1.45E+03	-0.730	
6	8.81E-04	1.06E+03	1.11E+03	-4.274	
7	1.10E-03	8.14E+02	8.49E+02	-4.062	
8	1.41E-03	6.13E+02	6.22E+02	-1.346	
9	1.80E-03	4.72E+02	4.64E+02	1.701	
10	2.22E-03	3.81E+02	3.60E+02	5.959	
11	2.80E-03	3.01E+02	2.74E+02	9.748	
12	3.55E-03	2.08E+02	2.09E+02	-0.474	
13	4.43E-03	1.56E+02	1.62E+02	-3.839	
14	5.64E-03	1.19E+02	1.24E+02	-3.962	
15	7.13E-03	9.24E+01	9.65E+01	-4.237	
16	8.81E-03	7.81E+01	7.70E+01	1.406	
17	1.10E-02	6.32E+01	6.15E+01	2.708	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
TDHZ ARRAY, 17 DATA POINTS, RAMP: 165.0 MICROSEC, DATA: WAIK1
2910 1111 1111 Z OPR XTL L 6 10+1000
Ch.21 = 0.165 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 2.39E-02, ANTILOG YIELDS 5.6524 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.97		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1

BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET
SOUNDING WAIK1
DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054 Figure 3-2

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The objectives of the geophysical survey for the State of Hawaii were to interpret from the individual TDEM soundings the resistivity layering as a function of depth. Also, to infer from the resistivity information the depth to salt water, and the thickness of the basal fresh water lens. The TDEM soundings were purposely acquired along traverse lines from about the 1,400 ft to 1,700 ft elevation level. The results of the individual soundings were used to construct geoelectric cross sections through several transects. From the 10 soundings taken on the area of interest, four geoelectric cross sections were constructed to display the interpreted data set. Figure 2-1 shows the locations of the soundings and the geoelectric cross sections.

Using available knowledge about the relation between resistivity values and local hydrogeology, geologic and geohydrologic information was inferred from geoelectric cross sections. The characteristic ranges of resistivities expected for local geohydrologic units in the survey area are shown in Figure 4-1. The resistivity range for ash flows, weathered volcanics or intrusives overlaps both the lower range of the dry unweathered or fresh/brackish water saturated volcanics and the upper range for salt water saturated volcanics. In many cases the geohydrologic units can be separated by their relative depth of occurrence in the section.

In the TDEM interpretation, where a very conductive layer (< 5 ohm-m) is detected below sea level, this layer is expected to be caused by salt water saturated volcanics. For this survey a fixed 2.8 ohm-m resistivity value was used to represent the resistivity of the salt water saturated layer. The validity of using this resistivity value for salt water saturated volcanics was confirmed by a previous TDEM survey in the Waikoloa area to the north. Static water levels (heads) can subsequently be calculated from these soundings by using the Ghyben-Herzberg principle. This principle states that under conditions of static equilibrium, for every foot of fresh water above sea level there will be about forty feet of fresh water below sea level. An illustration of the Ghyben-Herzberg principle is given in Figure 4-2. This principle, however, assumes static equilibrium and may not apply to TDEM sounding data in close proximity to ground water damming structures (i.e., dikes, rifts, etc.).

TDEM soundings in areas where ground water has been shown to be dike-confined, typically show high resistivity (greater than 100 ohm-m) layers to the exploration depth of the TDEM system (typically -800 ft below sea level). In other words, no sea water saturated formations are interpreted within the entire section. Within the structure controlled areas which separate the basal mode and dike-confined areas, TDEM data often exhibit intermediate resistivity values (10 to 100 ohm-m) that may occur both above and below sea level. In cases where intermediate resistivities occur well below sea level (-300 to -500 ft) it is generally not possible to determine the exact origin and nature of the subsurface conditions influencing the formation resistivities. The data taken in these areas may be distorted or influenced by the nearby structures and may not be diagnostic of true resistivity layering. This is due to the large subsurface areas that are averaged below a large transmitter loop (1,500 ft by 1,500 ft) and the limitation of present 1-D interpretations for TDEM data.

4.2 GEOELECTRIC CROSS SECTIONS

The results of the 10 TDEM sounding interpretations are presented as four geoelectric cross sections and are shown in Figures 4-3 and 4-4. Layers with similar resistivities have been linked together in the geoelectric sections.

Lines 1 and 2

The geoelectric cross sections for Lines 1 and 2 are both presented as northwest to southeast transects in Figure 4-3. Similar two-layer sequences are interpreted in the geoelectric cross sections for Lines 1 and 2. The upper layer of these two geoelectric cross sections exhibit high resistivities ranging from 2,857 ohm-m at sounding 3 to greater than 9,000 ohm-m at sounding 5 and are interpreted to represent unweathered volcanics. Below sea level, in both cross sections, this resistive layer is expected to be saturated with fresh/brackish water. The lower layer in both lines has been fixed to a 2.8 ohm-m resistivity and is interpreted to represent salt water saturated volcanics. The approximate thickness of the fresh/brackish water lens for these soundings was found to vary between 329 ft at sounding 1 to 430 ft beneath sounding 2.

Lines 3 and 4

In Figure 4-4 the geoelectric cross section for Lines 3 and 4 are displayed. The soundings were interpreted with either a two or three layer geoelectric section. The upper layer in both cross sections exhibits high resistivity values ranging from 1,312 ohm-m to greater than 6,000 ohm-m. This upper layer at soundings 7, 3 and 4 is interpreted to represent dry unweathered volcanics above sea level, and where it occurs below sea level, it is expected to be saturated with fresh/brackish basal mode water. The lower layer of Line 3 (and sounding 8 on Line 4) exhibits intermediate resistivity values ranging from 9.2 ohm-m to 71 ohm-m. This lower layer may be caused by changes in lithology (ash flows, weathered volcanics), changes in water quality or geologic structure.

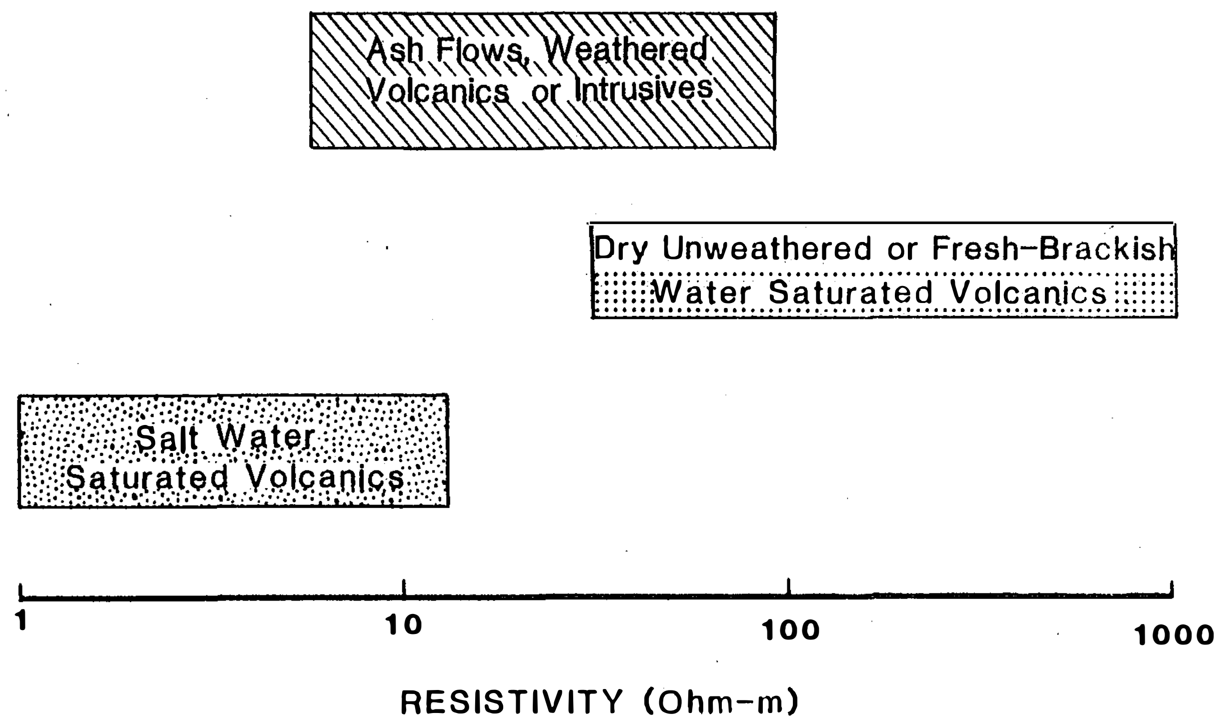
Beneath soundings 3, 4 and 7 of Line 4 where the lower layer is interpreted to represent salt water saturated volcanics, the approximate thickness of the fresh/brackish water lens can be estimated from these soundings and it was found to vary from 344 ft at sounding 4 to 396 ft at sounding 7. Because of the rapid resistivity contrasts between soundings 7 and 8 (2.8 ohm-m to 71 ohm-m) lateral changes are expected to occur between the two soundings and a geologic structure is inferred.

4.3 HYDROGEOLOGIC INTERPRETATIONS

Table 4-2 lists the approximate thickness of the fresh/brackish water lens calculated from the elevation of the salt water interface interpreted from the individual TDEM soundings. The table includes the value of static water level (head) calculated by using the Ghyben-Herzberg principle.

Table 4-1. Hydrogeologic information derived from TDEM soundings (values in ft)

Sounding #	Surface Elevation	Elevation of Salt Water	Calculated Static Water Level (head)	Approximate Thickness of Fresh/ Brackish Water Lens
1	1400	-329	8	337
2	1505	-430	11	441
3	1645	-390	10	400
4	1560	-344	9	353
5	1405	-345	9	354
6	1560	-422	11	433
7	1660	-396	10	406
8	1720	Not Detected	N/A	N/A
9	1525	Not Detected	N/A	N/A
10	1400	Not Detected	N/A	N/A



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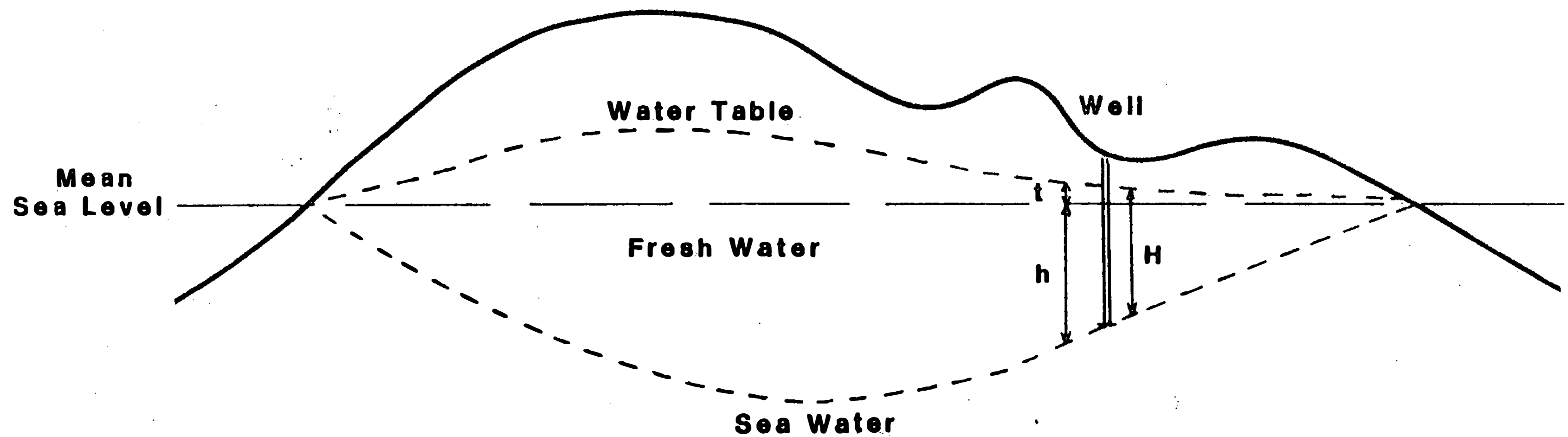
CHARACTERISTIC RESISTIVITY RANGES

DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054 **Figure 4-1**



$$t = 1/40\ (h)$$

FROM: HERZBERG

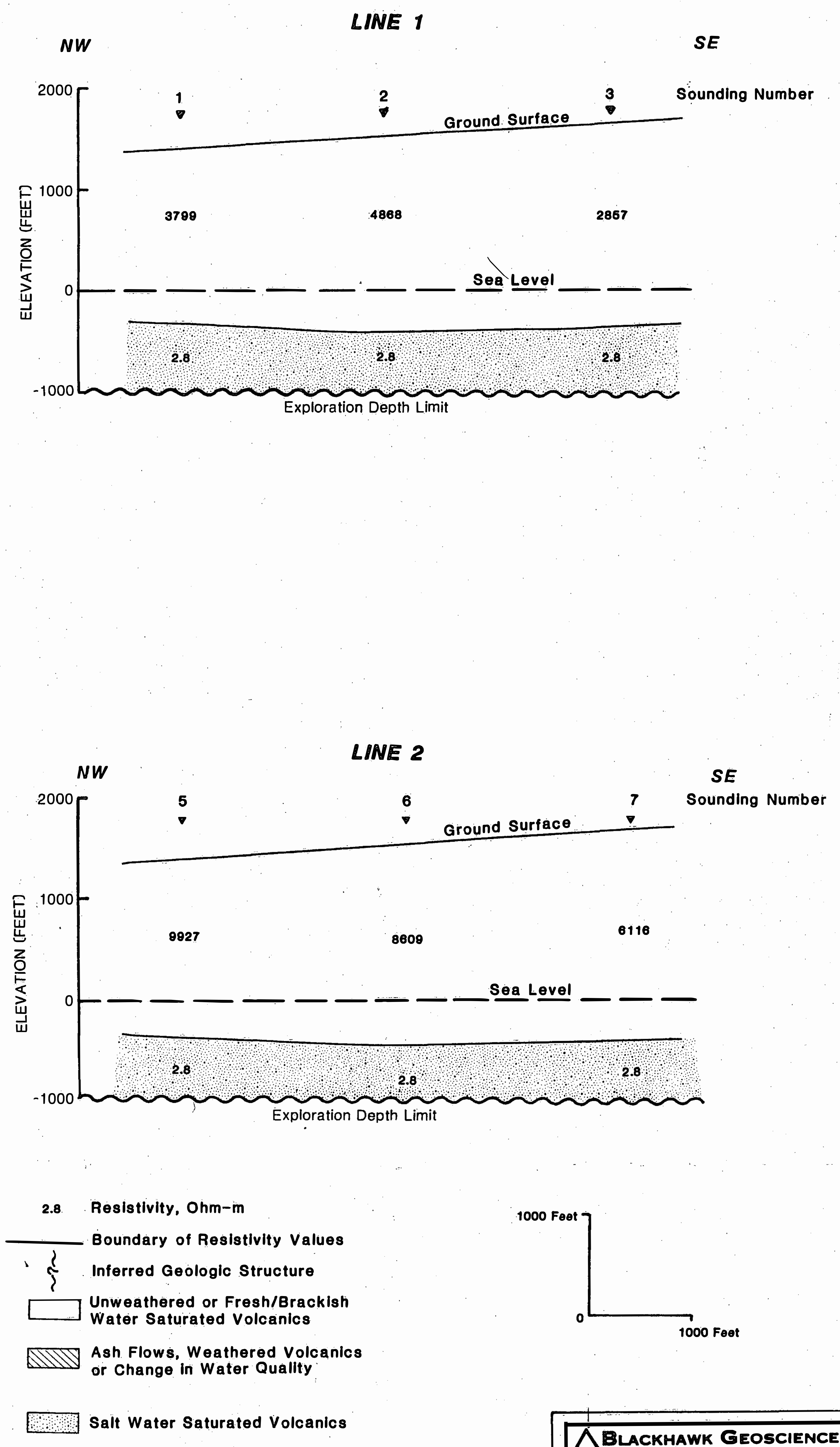
BLACKHAWK GEOSCIENCES, INC.

Illustration of the
Ghyben-Herzberg Principle

DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054

Figure 4-2



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GEOELECTRIC CROSS SECTION
LINES 1 AND 2
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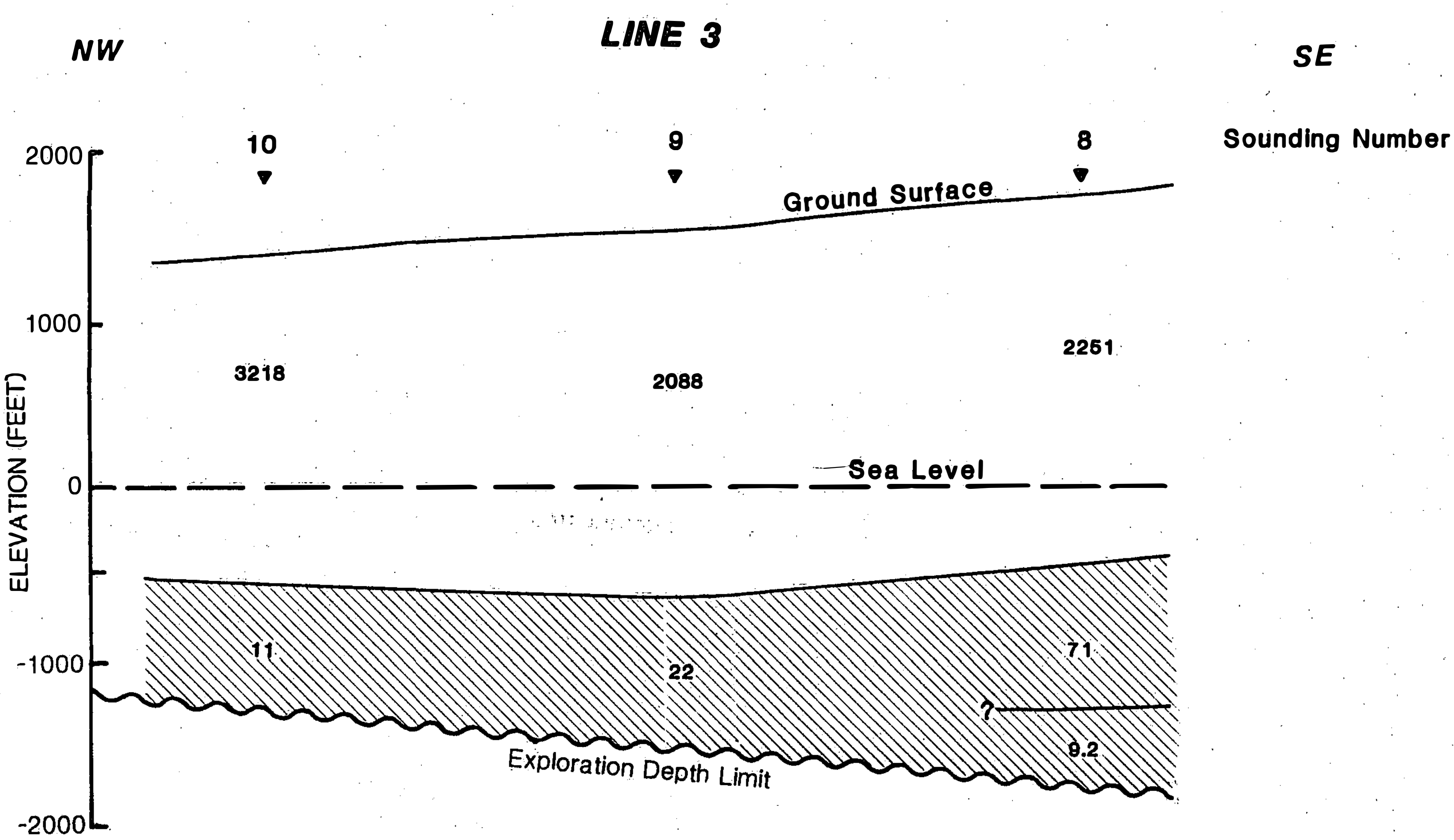
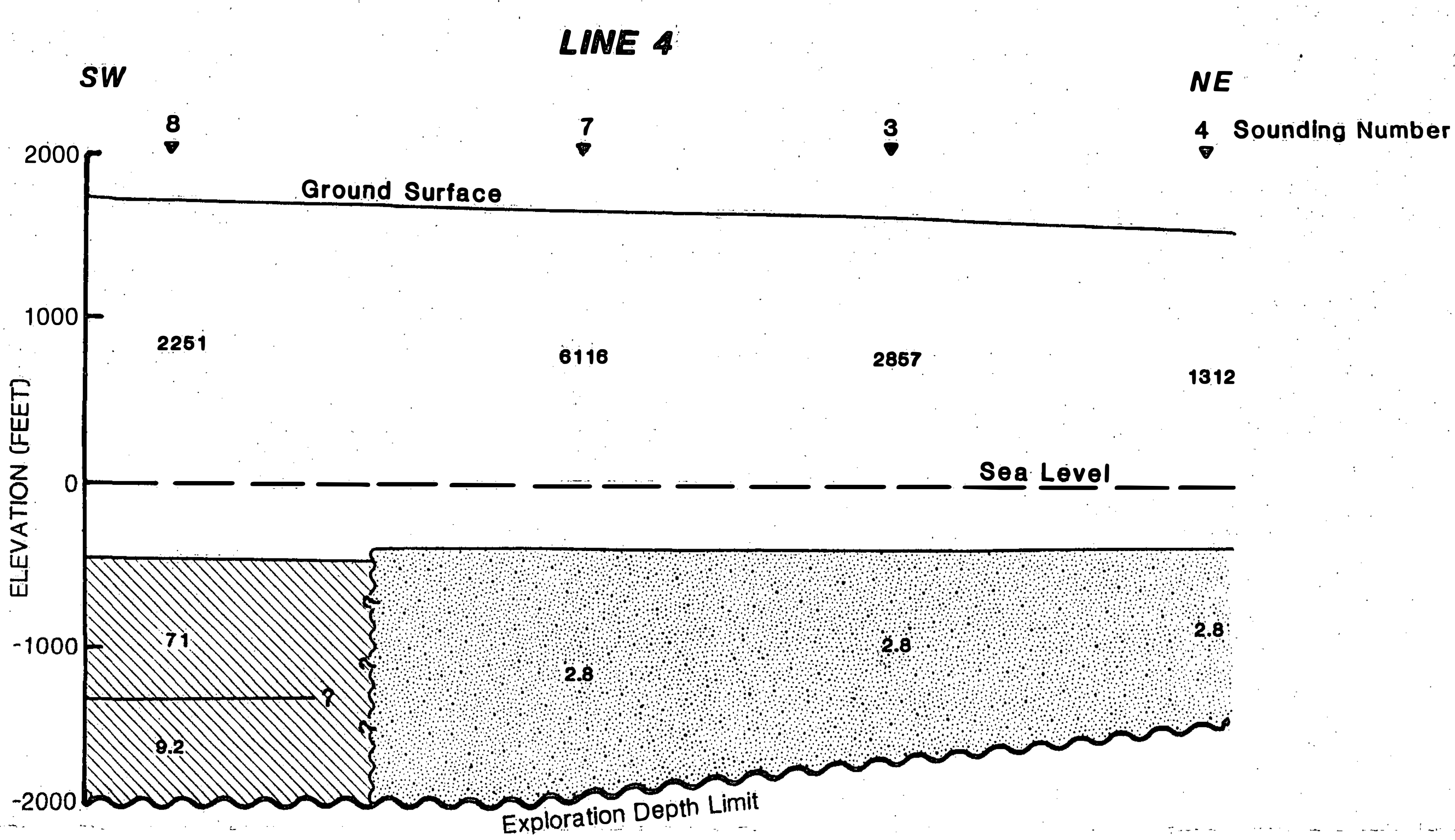
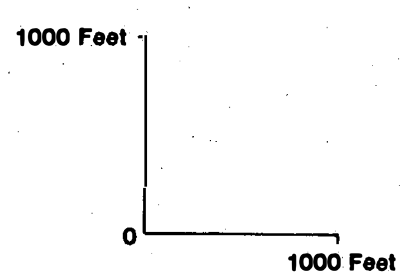
STATE OF HAWAII

PROJECT NO: 91054

Figure 4-3







2.8 Resistivity, Ohm-m

Boundary of Resistivity Values

Inferred Geologic Structure

Unweathered or Fresh/Brackish Water Saturated Volcanics

Ash Flows, Weathered Volcanics or Change in Water Quality

Salt Water Saturated Volcanics

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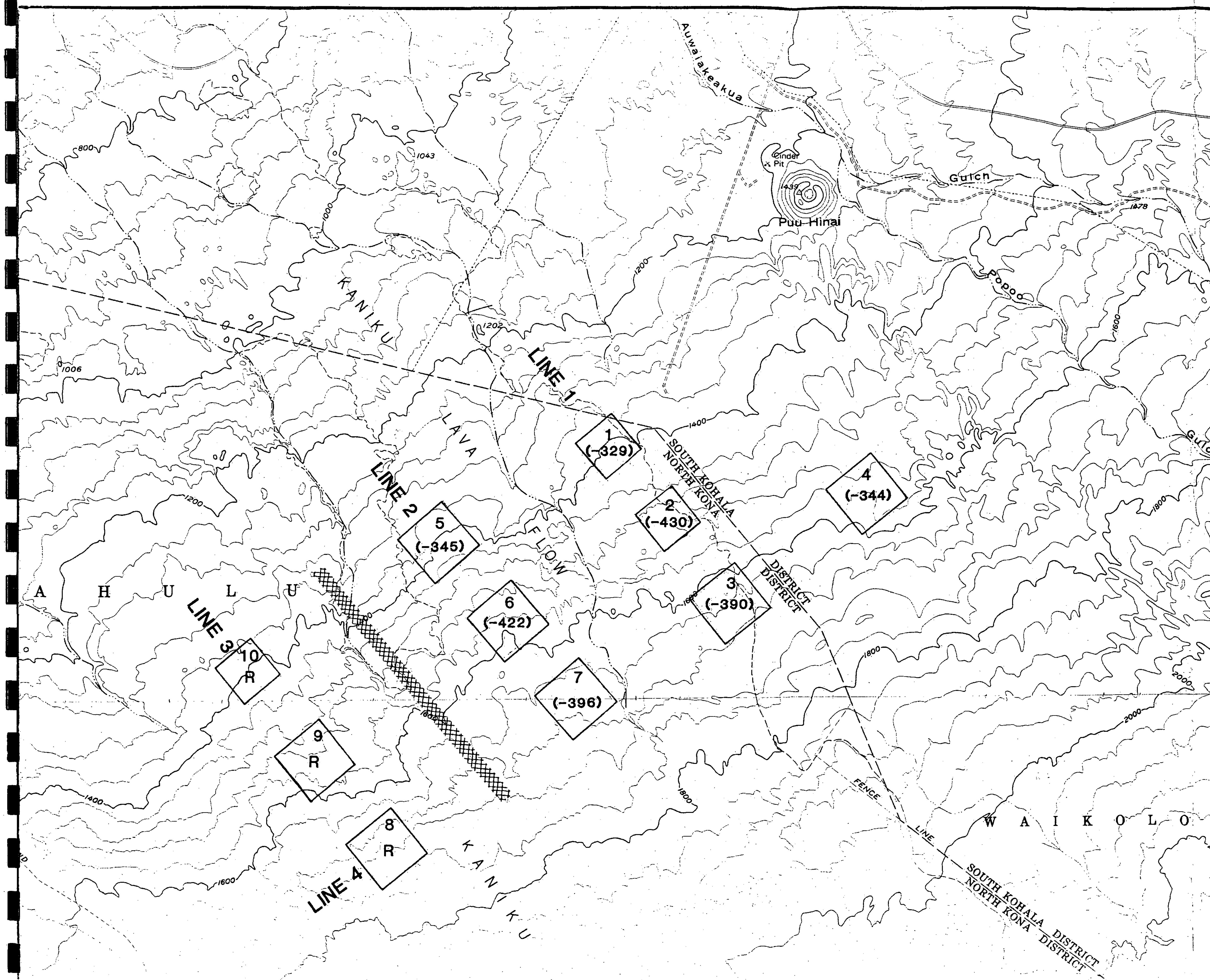
GEOELECTRIC CROSS SECTION
LINES 3 AND 4

DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054 | Figure 4-4



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TDEM INTERPRETATION MAP

DIVISION OF WATER RESOURCES MGMT.
STATE OF HAWAII

PROJECT NO: 91054

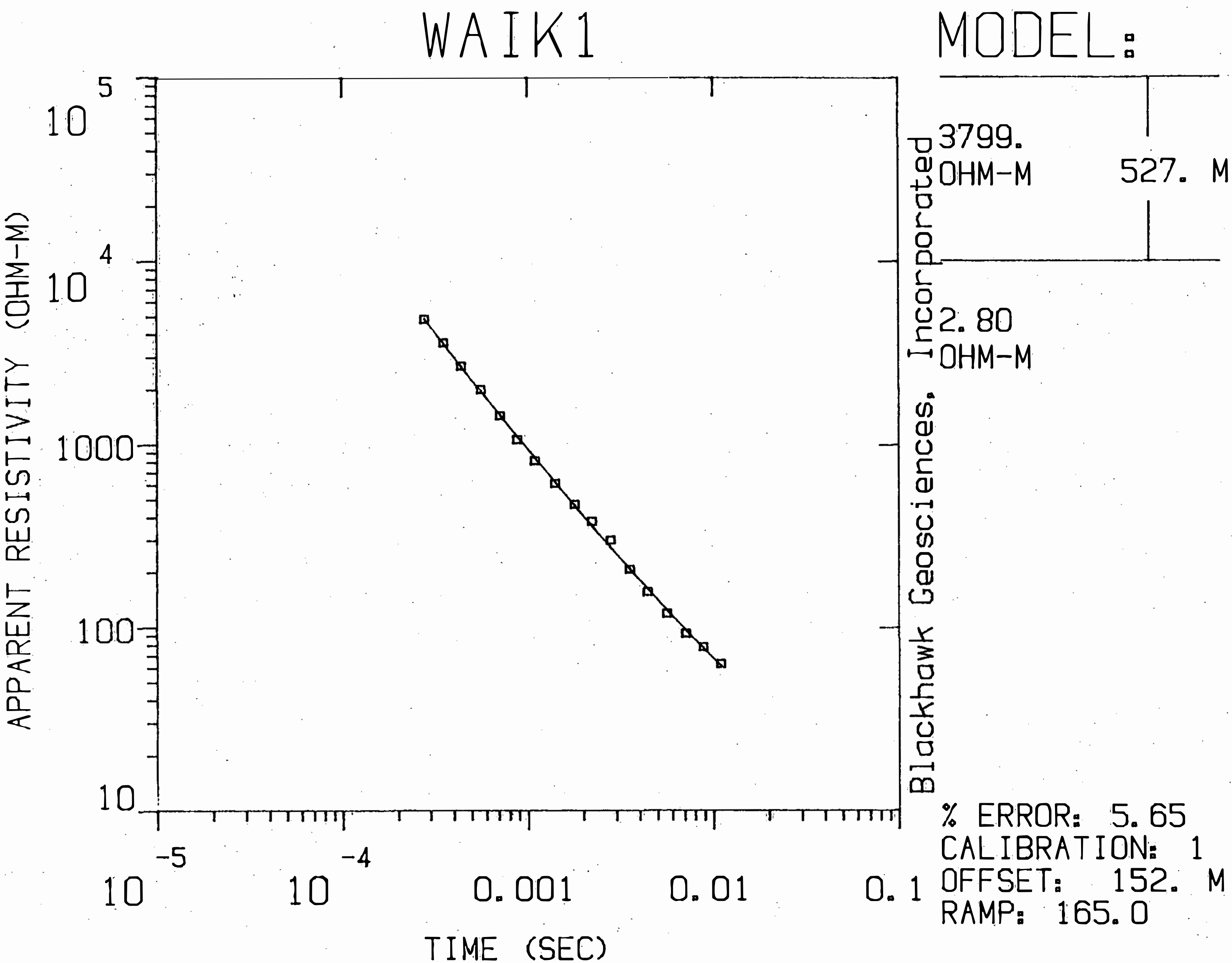
Figure 4-5

5.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM survey was to assist in the ground water resource evaluation of the Puu Anahulu area of North Kona, Hawaii. The results of the TDEM survey are summarized in Figures 4-3, 4-4 and 4-5. As shown in Figure 4-5 (beneath soundings 1 through 7), salt water saturated volcanics were detected at depth and fresh/brackish ground water resources are expected to be present in the basal mode. The thickness of the basal fresh/brackish water lens is expected to vary from about 329 ft to 430 ft. Beneath soundings along Line 3 (10, 9 and 8) salt water saturated volcanics were not detected. The intermediate to high resistivity layer detected below sea level on these soundings may be caused by lithologic, geologic, or hydrologic variations and thus, estimates of available ground water resources cannot be made for these soundings. The depth and resistivities of the lower layer in these soundings display some similarities to soundings taken on previous surveys near a ground water damming structure. Thus, the potential for significant ground water resources may be present up-gradient of the structure if other favorable subsurface conditions exist, such as high porosity and permeability.

The location of the boundary between areas with basal mode ground water resources and areas where a resistive basement was detected is not accurately determined because of the large distances between lines and soundings in this vicinity of the study area. To better define the boundary location and its relative direction, additional soundings between Line 2 and Line 3 are recommended. To determine if high level ground water resources exist southwest of Line 3, additional soundings are recommended in this area.

The relative accuracy in determining the depth to the salt water saturated interface is expected to be about $\pm$ 5% of the total depth measured.



WAIK1
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
3799.
OHM-M
527. M
2.80
OHM-M
Blackhawk Geosciences, Incorporated
% ERROR: 5.65
CALIBRATION: 1
OFFSET: 152. M
RAMP: 165.0

WAIK1

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		426.7	1400.0		
3799.13	527.1	-100.3	-329.2	0.1	0.1
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.80E-04	4.83E+03	4.86E+03	-0.654	
2	3.55E-04	3.60E+03	3.56E+03	1.050	
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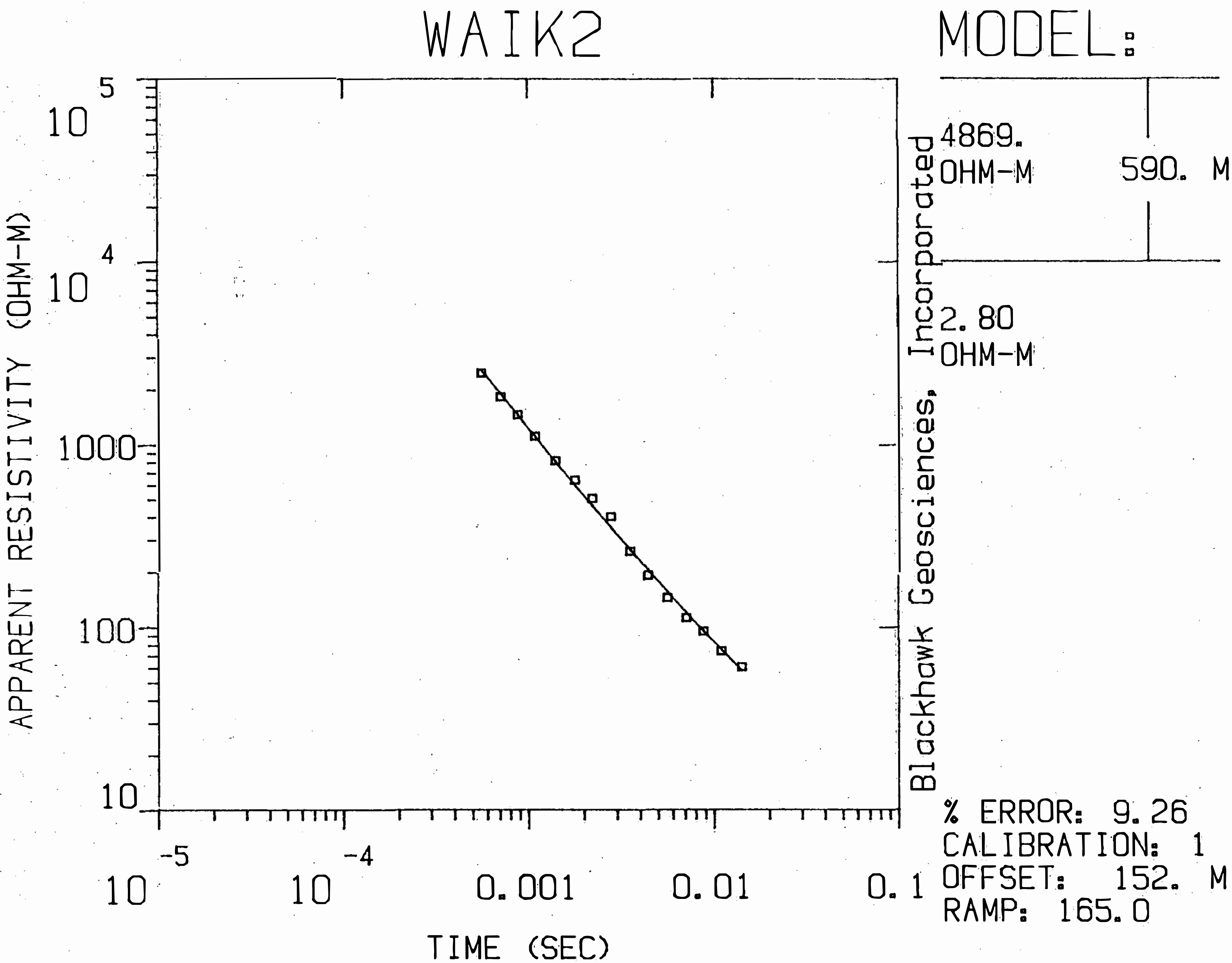
8	1.41E-03	6.13E+02	6.22E+02	-1.346	
9	1.80E-03	4.72E+02	4.64E+02	1.701	
10	2.22E-03	3.81E+02	3.60E+02	5.959	
11	2.80E-03	3.01E+02	2.74E+02	9.748	
12	3.55E-03	2.08E+02	2.09E+02	-0.474	
13	4.43E-03	1.56E+02	1.62E+02	-3.839	
14	5.64E-03	1.19E+02	1.24E+02	-3.962	
15	7.13E-03	9.24E+01	9.65E+01	-4.237	
16	8.81E-03	7.81E+01	7.70E+01	1.406	
17	1.10E-02	6.32E+01	6.15E+01	2.708	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
TDHZ ARRAY, 17 DATA POINTS, RAMP: 165.0 MICROSEC, DATA: WAIK1
2910 1111 1111 Z OPR XTL L 6 10+1000
Ch.21 = 0.165 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 2.39E-02, ANTILOG YIELDS 5.6524 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.97		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1



WAIK2
MODEL:
4869.
OHM-M
590. M
2.80
OHM-M
Blackhawk Geosciences, Incorporated
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
% ERROR: 9.26
CALIBRATION: 1
OFFSET: 152. M
RAMP: 165.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		458.7	1505.0		
4868.63	589.8	-131.1	-430.2	0.1	0.1
2.80					

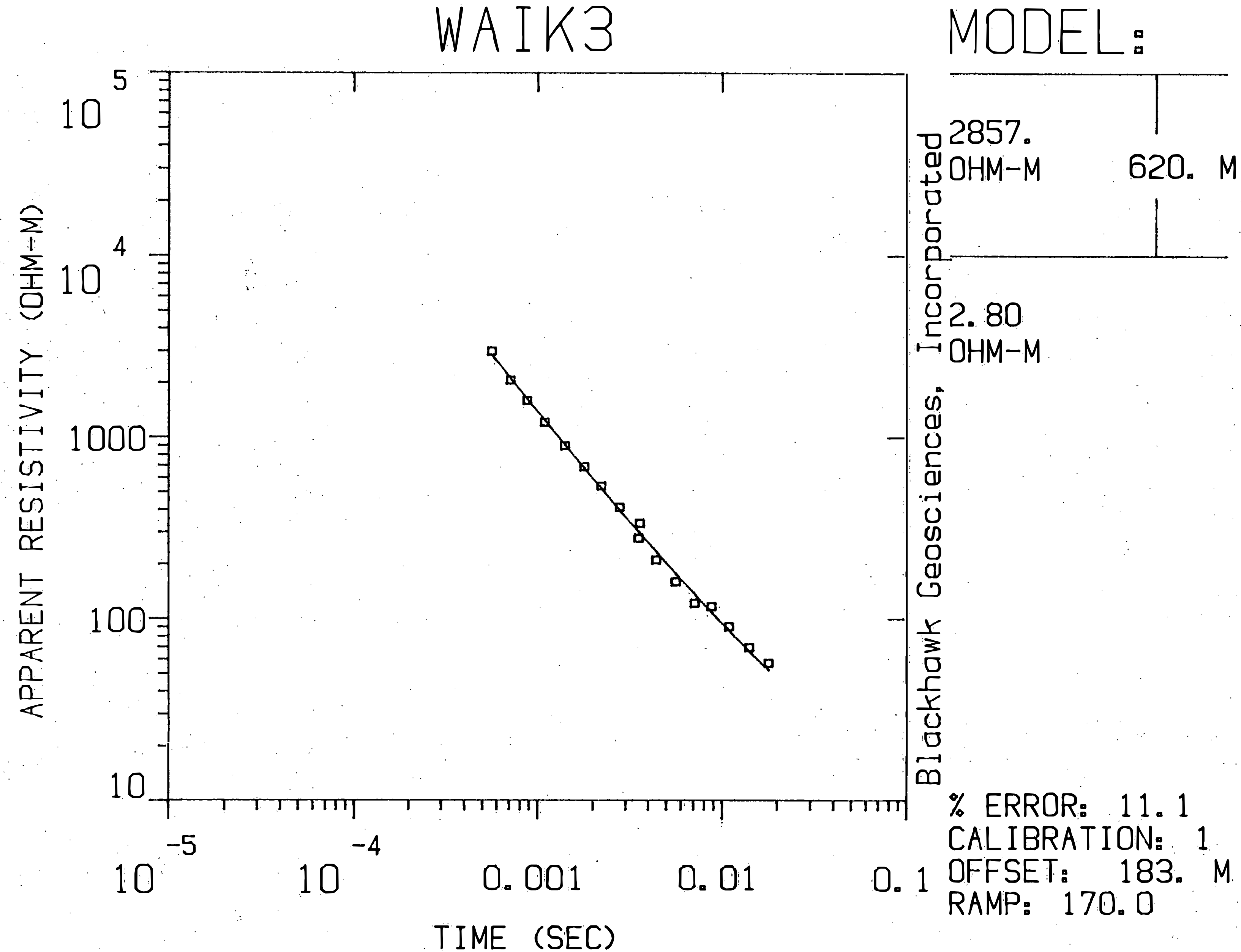
	TIMES	DATA	CALC	% ERROR	STD ERR
1	5.64E-04	2.46E+03	2.58E+03	-4.373	
2	7.13E-04	1.82E+03	1.90E+03	-4.246	
3	8.81E-04	1.46E+03	1.46E+03	-0.163	
4	1.10E-03	1.11E+03	1.11E+03	0.603	
5	1.41E-03	8.18E+02	8.08E+02	1.157	
6	1.80E-03	6.39E+02	6.02E+02	6.170	
7	2.22E-03	5.07E+02	4.63E+02	9.435	
8	2.80E-03	4.02E+02	3.52E+02	14.250	
9	3.55E-03	2.59E+02	2.66E+02	-2.594	
10	4.43E-03	1.92E+02	2.06E+02	-6.940	
11	5.64E-03	1.45E+02	1.56E+02	-7.452	
12	7.13E-03	1.13E+02	1.20E+02	-6.319	
13	8.81E-03	9.49E+01	9.53E+01	-0.459	
14	1.10E-02	7.40E+01	7.55E+01	-1.915	
15	1.41E-02	6.07E+01	5.79E+01	4.901	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
TDHZ ARRAY, 15 DATA POINTS, RAMP: 165.0 MICROSEC, DATA: WAIK2
2910 1111 2222 Z OPR XTL L 6 10+1000
Ch.21 = 0.165 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 3.85E-02, ANTILOG YIELDS 9.2633 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.04		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1


WAIK3
MODEL:
2857.
OHM-M
620. M
2.80
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 11.1
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0

WAIK3

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		501.4	1645.0		
2857.34	620.1	-118.7	-389.6	0.2	0.2
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	5.64E-04	2.98E+03	2.86E+03	4.063	
2	7.13E-04	2.06E+03	2.13E+03	-3.195	
3	8.81E-04	1.59E+03	1.63E+03	-2.487	
4	1.10E-03	1.20E+03	1.24E+03	-2.986	
5	1.41E-03	8.95E+02	9.10E+02	-1.572	
6	1.80E-03	6.87E+02	6.76E+02	1.615	
7	2.22E-03	5.40E+02	5.23E+02	3.206	
8	2.80E-03	4.13E+02	3.97E+02	3.961	
9	3.55E-03	2.76E+02	3.00E+02	-8.063	
10	3.60E-03	3.36E+02	2.96E+02	13.669	
11	4.43E-03	2.10E+02	2.33E+02	-9.979	
12	5.64E-03	1.59E+02	1.77E+02	-10.052	
13	7.13E-03	1.22E+02	1.36E+02	-10.851	
14	8.81E-03	1.17E+02	1.08E+02	7.517	
15	1.10E-02	9.02E+01	8.60E+01	4.876	
16	1.41E-02	6.95E+01	6.65E+01	4.584	
17	1.80E-02	5.71E+01	5.22E+01	9.383	

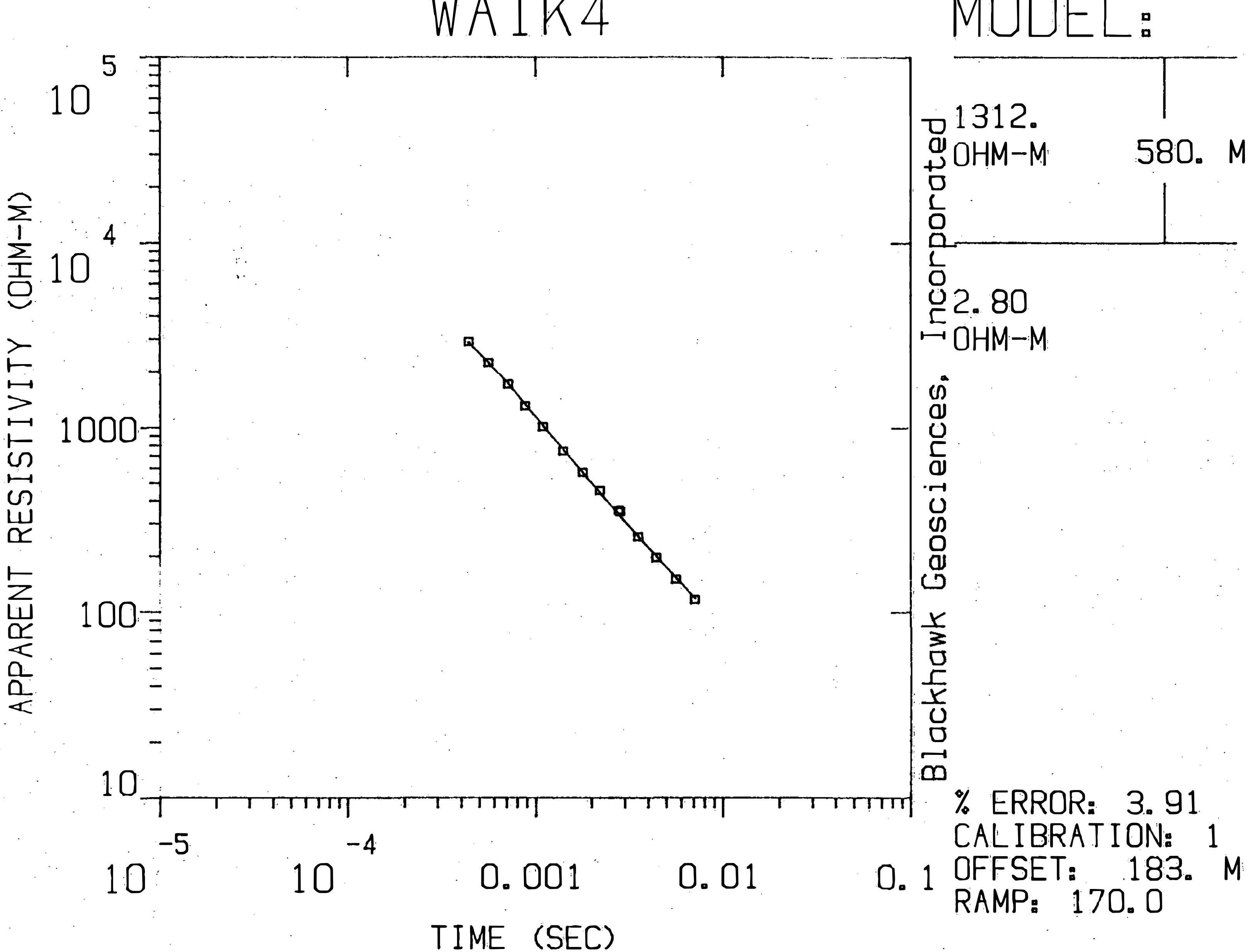
R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 17 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK3
3010 1111 0003 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 4.57E-02, ANTILOG YIELDS 11.1009 %
LATE TIME PARAMETERS

/

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER
P 1 0.75
F 2 0.00 0.00
T 1 0.00 0.00 1.00
P 1 F 2 T 1

WAIK4



MODEL:
1312.
OHM-M
580. M
2.80
OHM-M
% ERROR: 3.91
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
Blackhawk Geosciences, Incorporated

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		475.5	1560.0		
1312.34	580.3	-104.8	-343.8	0.4	0.4
2.80					

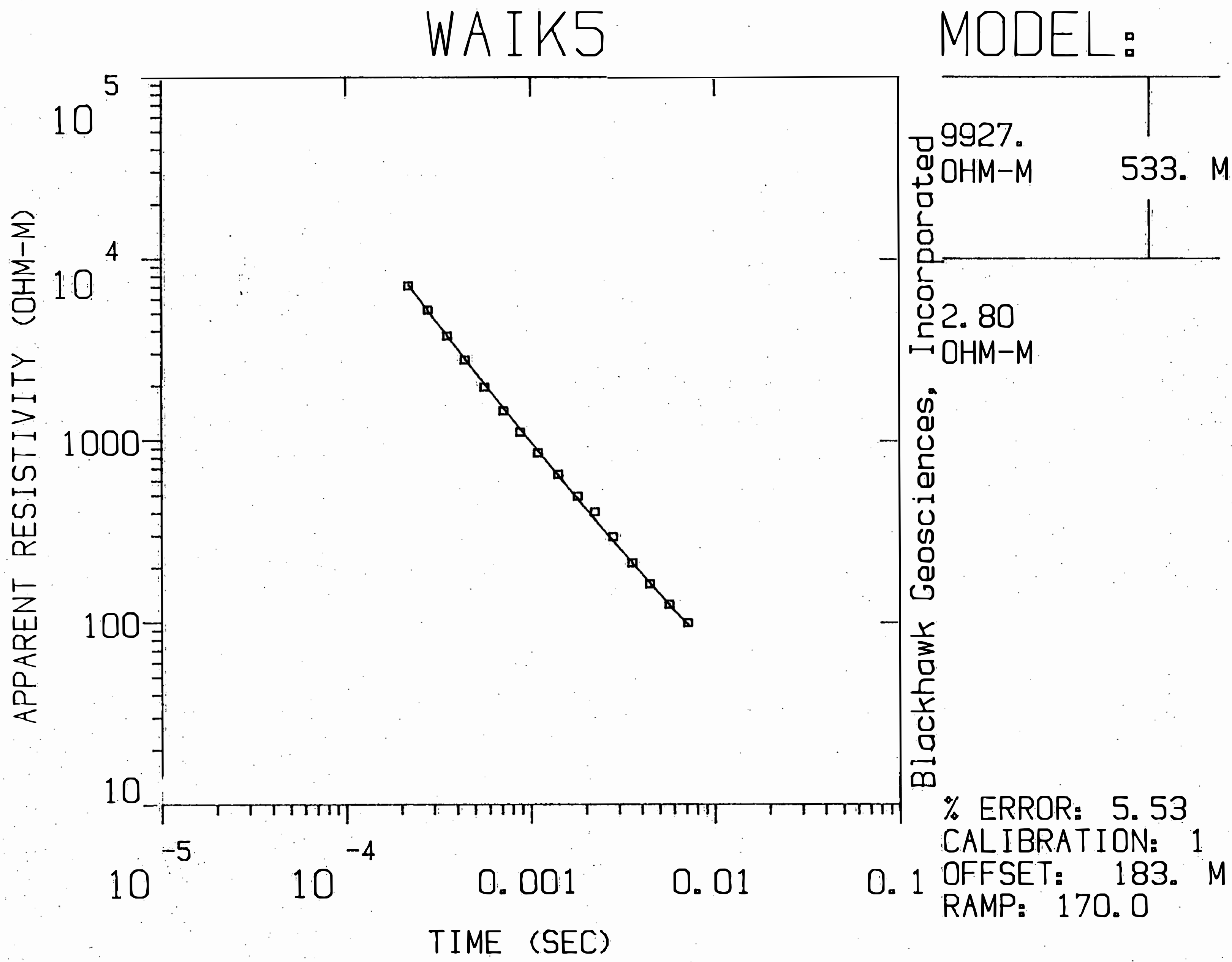
	TIMES	DATA	CALC	% ERROR	STD ERR
1	4.43E-04	2.91E+03	2.88E+03	0.879	
2	5.64E-04	2.24E+03	2.25E+03	-0.463	
3	7.13E-04	1.72E+03	1.75E+03	-1.338	
4	8.81E-04	1.31E+03	1.34E+03	-2.021	
5	1.10E-03	1.01E+03	1.03E+03	-1.556	
6	1.41E-03	7.46E+02	7.61E+02	-1.954	
7	1.80E-03	5.71E+02	5.71E+02	0.002	
8	2.22E-03	4.57E+02	4.42E+02	3.356	
9	2.80E-03	3.56E+02	3.38E+02	5.114	
10	2.85E-03	3.50E+02	3.32E+02	5.489	
11	3.55E-03	2.55E+02	2.57E+02	-0.905	
12	4.43E-03	1.95E+02	2.00E+02	-2.287	
13	5.64E-03	1.50E+02	1.53E+02	-2.154	
14	7.13E-03	1.16E+02	1.19E+02	-1.748	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 14 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK4
3010 0000 0003 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 1.67E-02, ANTILOG YIELDS 3.9130 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1



WAIK5
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
9927.
OHM-M
533. M
2.80
OHM-M
% ERROR: 5.53
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0

WAIK5

MODEL: 2 LAYERS

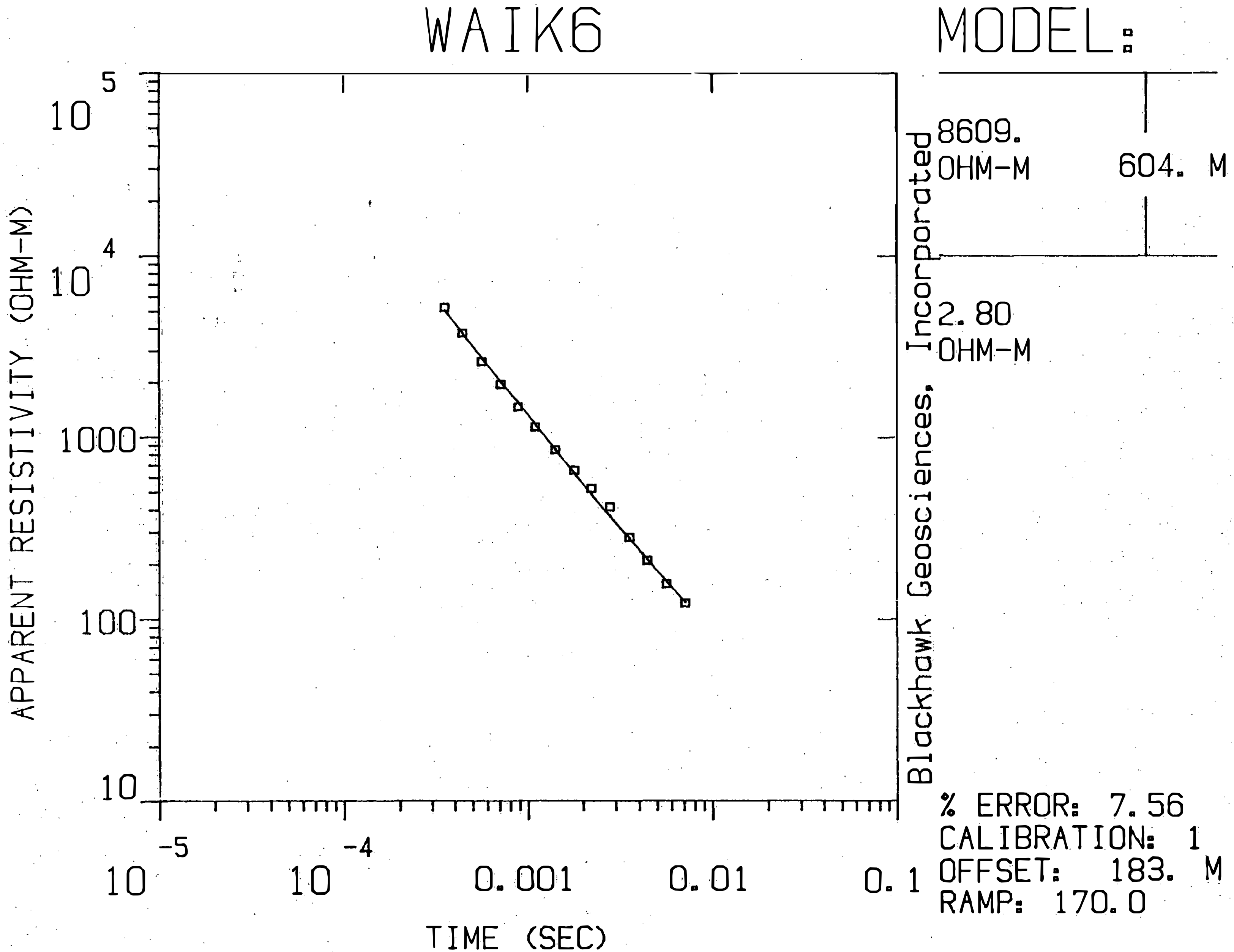
RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		428.2	1405.0		
9926.62	533.5	-105.2	-345.2	0.1	0.1
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.20E-04	7.09E+03	7.18E+03	-1.178	
2	2.80E-04	5.22E+03	5.18E+03	0.830	
3	3.55E-04	3.75E+03	3.77E+03	-0.512	
4	4.43E-04	2.76E+03	2.81E+03	-1.835	
5	5.64E-04	1.97E+03	2.05E+03	-4.313	
6	7.13E-04	1.45E+03	1.52E+03	-4.271	
7	8.81E-04	1.11E+03	1.16E+03	-4.325	
8	1.10E-03	8.53E+02	8.81E+02	-3.171	
9	1.41E-03	6.51E+02	6.43E+02	1.373	
10	1.80E-03	4.94E+02	4.78E+02	3.279	
11	2.22E-03	4.05E+02	3.69E+02	9.608	
12	2.80E-03	2.95E+02	2.81E+02	5.313	
13	3.55E-03	2.12E+02	2.13E+02	-0.346	
14	4.43E-03	1.62E+02	1.65E+02	-1.389	
15	5.64E-03	1.25E+02	1.25E+02	0.186	
16	7.13E-03	9.91E+01	9.66E+01	2.611	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 16 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK5
1031 2222 0005 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 2.34E-02, ANTILOG YIELDS 5.5321 %
LATE TIME PARAMETERS

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

```
P 1   0.00
F 2   0.00   0.00
T 1  -0.01   0.00   0.50
       P 1    F 2    T 1
```


WAIK6
MODEL:
8609.
OHM-M
604. M
2.80
OHM-M
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
Blackhawk Geosciences, Incorporated
% ERROR: 7.56
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0

WAIK6

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		475.5	1560.0		
8609.00	604.3	-128.8	-422.5	0.1	0.1
2.80					

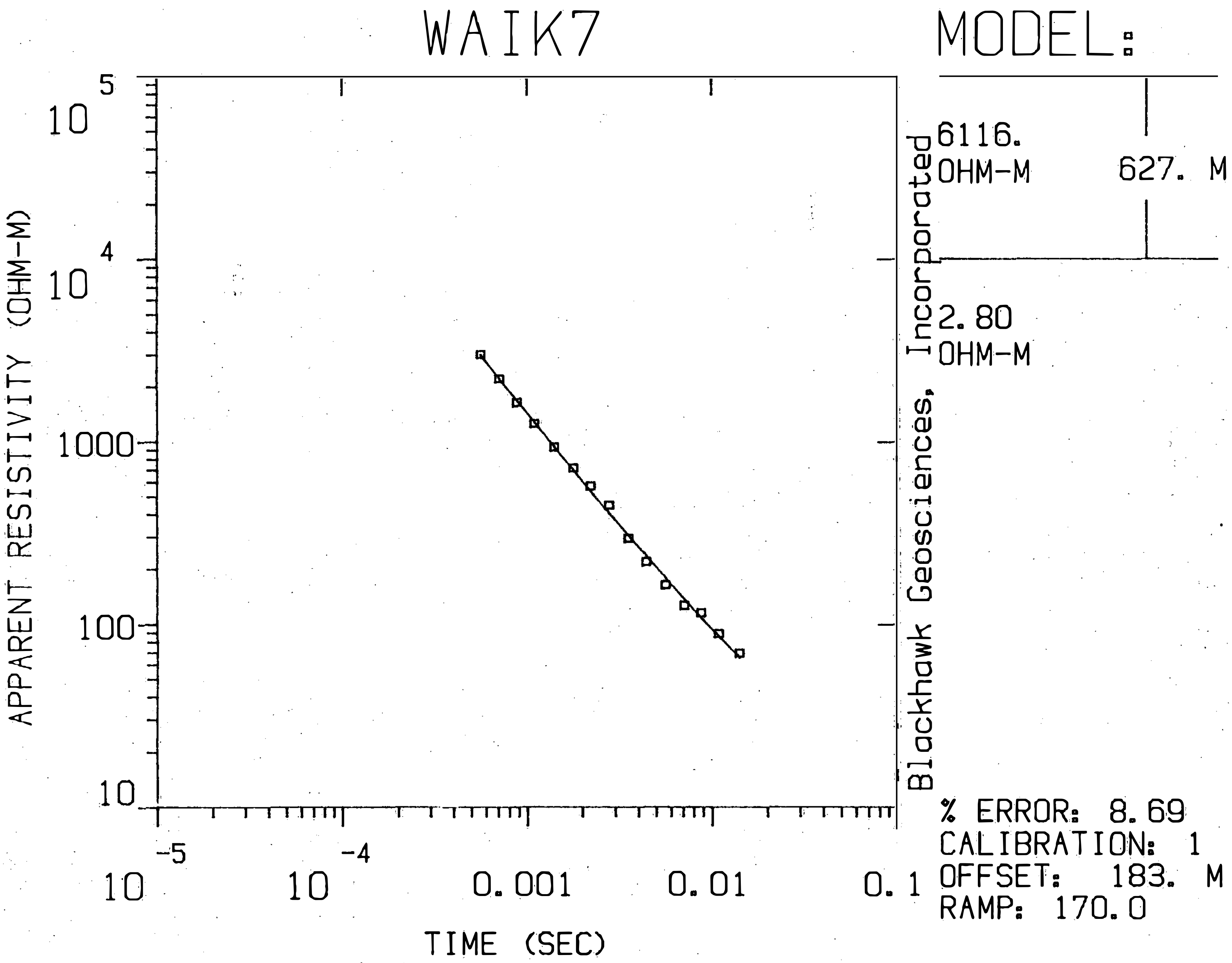
	TIMES	DATA	CALC	% ERROR	STD ERR
1	3.55E-04	3.23E+03	3.07E+03	3.178	
2	4.43E-04	3.77E+03	3.78E+03	-0.290	
3	5.64E-04	2.61E+03	2.75E+03	-5.043	
4	7.13E-04	1.95E+03	2.04E+03	-4.146	
5	8.81E-04	1.46E+03	1.55E+03	-5.663	
6	1.10E-03	1.13E+03	1.17E+03	-3.808	
7	1.41E-03	8.48E+02	8.56E+02	-0.922	
8	1.80E-03	6.58E+02	6.34E+02	3.826	
9	2.22E-03	5.25E+02	4.88E+02	7.605	
10	2.80E-03	4.15E+02	3.69E+02	12.571	
11	3.55E-03	2.81E+02	2.78E+02	1.282	
12	4.43E-03	2.10E+02	2.14E+02	-2.166	
13	5.64E-03	1.56E+02	1.62E+02	-3.240	
14	7.13E-03	1.22E+02	1.24E+02	-1.049	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 14 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK6
1031 2222 0006 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 3.17E-02, ANTILOG YIELDS 7.5650 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.03		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1


WAIK7
MODEL:
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
Blackhawk Geosciences, Incorporated
6116.
OHM-M
627. M
2.80
OHM-M
% ERROR: 8.69
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0

WAIK7

MODEL: 2 LAYERS

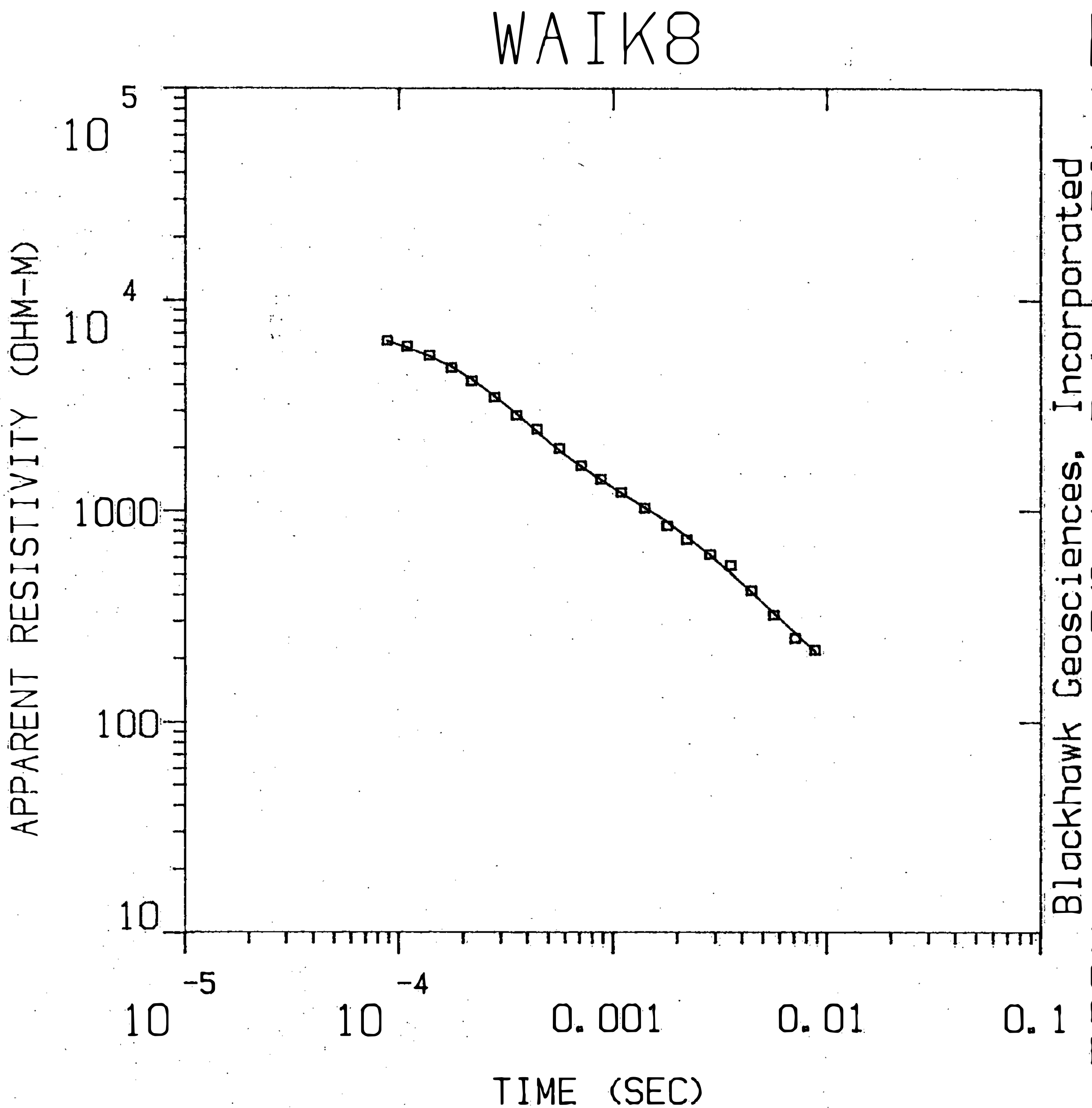
RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		506.0	1660.0		
6116.43	626.5	-120.5	-395.5	0.1	0.1
2.80					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	5.64E-04	3.01E+03	3.01E+03	0.160	
2	7.13E-04	2.22E+03	2.22E+03	-0.073	
3	8.81E-04	1.64E+03	1.69E+03	-3.030	
4	1.10E-03	1.26E+03	1.29E+03	-2.298	
5	1.41E-03	9.35E+02	9.36E+02	-0.179	
6	1.80E-03	7.16E+02	6.97E+02	2.779	
7	2.22E-03	5.72E+02	5.36E+02	6.805	
8	2.80E-03	4.49E+02	4.05E+02	10.690	
9	3.55E-03	2.95E+02	3.06E+02	-3.715	
10	4.43E-03	2.19E+02	2.36E+02	-7.178	
11	5.64E-03	1.64E+02	1.79E+02	-8.462	
12	7.13E-03	1.27E+02	1.37E+02	-7.552	
13	8.81E-03	1.16E+02	1.09E+02	6.667	
14	1.10E-02	8.89E+01	8.58E+01	3.509	
15	1.41E-02	6.94E+01	6.57E+01	5.692	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 15 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK7
1102 0002 0007 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 3.62E-02, ANTILOG YIELDS 8.6887 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER
P 1 0.03
F 2 0.00 0.00
T 1 -0.03 0.00 0.98
P 1 F 2 T 1



MODEL:

2251. OHM-M 670. M

70.8 OHM-M 273. M

9.21 OHM-M

% ERROR: 4.33
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		524.3	1720.0		
2250.81	669.8	-145.5	-477.4	0.3	0.3
70.77	272.7	-418.2	-1371.9	3.9	4.2
9.21					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	6.42E+03	6.41E+03	0.124	
2	1.10E-04	6.04E+03	5.96E+03	1.374	
3	1.40E-04	5.47E+03	5.43E+03	0.790	
4	1.77E-04	4.79E+03	4.85E+03	-1.380	
5	2.20E-04	4.14E+03	4.24E+03	-2.145	
6	2.80E-04	3.47E+03	3.52E+03	-1.532	
7	3.55E-04	2.84E+03	2.89E+03	-1.781	
8	4.43E-04	2.44E+03	2.38E+03	2.717	
9	5.64E-04	1.98E+03	1.93E+03	2.351	
10	7.13E-04	1.64E+03	1.62E+03	0.964	
11	8.81E-04	1.41E+03	1.40E+03	0.589	
12	1.10E-03	1.22E+03	1.21E+03	0.997	
13	1.41E-03	1.03E+03	1.03E+03	-0.409	
14	1.80E-03	8.47E+02	8.86E+02	-4.382	
15	2.22E-03	7.28E+02	7.51E+02	-3.034	
16	2.85E-03	6.21E+02	6.15E+02	0.912	
17	3.55E-03	5.51E+02	5.07E+02	8.563	
18	4.43E-03	4.18E+02	4.12E+02	1.452	
19	5.64E-03	3.20E+02	3.28E+02	-2.459	
20	7.13E-03	2.48E+02	2.62E+02	-5.271	
21	8.81E-03	2.18E+02	2.15E+02	1.677	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 21 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK8
1102 0003 0008 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 1.84E-02, ANTILOG YIELDS 4.3339 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

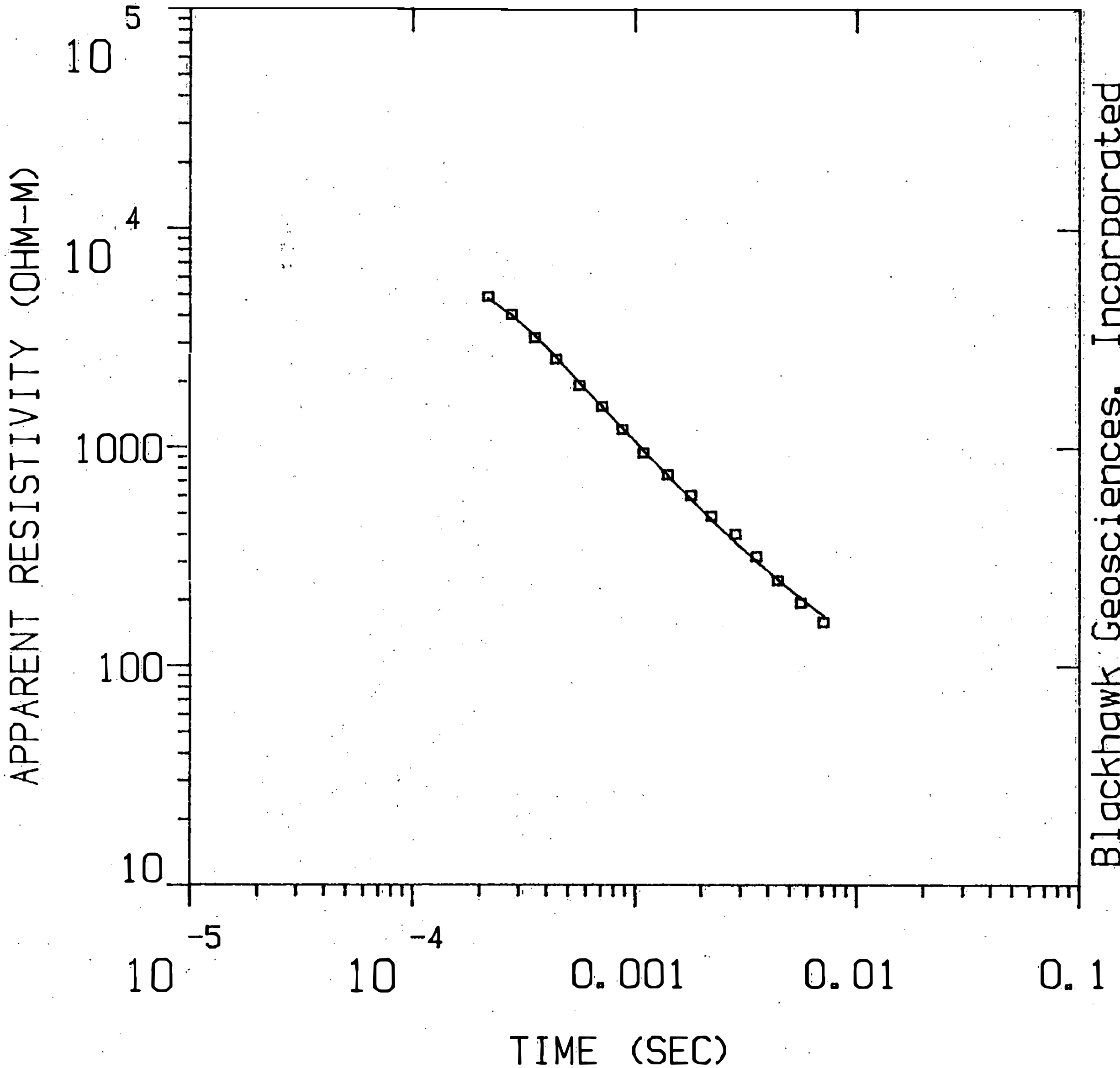
P 1	0.11				
P 2	-0.01	0.02			
P 3	0.00	-0.01	0.00		
T 1	0.03	0.06	-0.03	0.44	
T 2	-0.01	-0.01	0.00	-0.02	0.03
	P 1	P 2	P 3	T 1	T 2

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

[illegible]

RHO	1	2171.217	2252.811	2336.156
	2	63.426	70.772	78.463
	3	7.348	9.208	11.726
THICK	1	660.542	669.764	678.938
	2	253.088	272.656	292.777
DEPTH	1	660.542	669.764	678.938
	2	921.907	942.420	963.446

WAIK9



MODEL:

2088.
OHM-M

656. M

21.8
OHM-M

% ERROR: 5.87
CALIBRATION: 1
OFFSET: 183. M
RAMP: 170.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		464.8	1525.0		
2088.39	655.8	-191.0	-626.6	0.3	0.3
21.79					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.20E-04	4.87E+03	4.80E+03	1.423	
2	2.80E-04	4.05E+03	4.02E+03	0.663	
3	3.55E-04	3.17E+03	3.26E+03	-2.765	
4	4.43E-04	2.53E+03	2.60E+03	-2.649	
5	5.64E-04	1.92E+03	1.98E+03	-3.157	
6	7.13E-04	1.54E+03	1.54E+03	0.025	
7	8.81E-04	1.20E+03	1.22E+03	-1.617	
8	1.10E-03	9.41E+02	9.67E+02	-2.605	
9	1.41E-03	7.50E+02	7.40E+02	1.341	
10	1.80E-03	6.04E+02	5.81E+02	3.999	
11	2.22E-03	4.87E+02	4.69E+02	3.957	
12	2.85E-03	4.03E+02	3.70E+02	8.923	
13	3.55E-03	3.18E+02	3.03E+02	5.053	
14	4.43E-03	2.46E+02	2.49E+02	-0.926	
15	5.64E-03	1.94E+02	2.04E+02	-4.752	
16	7.13E-03	1.59E+02	1.69E+02	-6.135	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
TDHZ ARRAY, 16 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK9
1103 0003 0009 Z OPR XTL L 7 10+1000
Ch.21 = 0.17 Ch.22 = 0.89 Ch.23 = 13 Ch.24 = 13
RMS LOG ERROR: 2.48E-02, ANTILOG YIELDS 5.8733 %
LATE TIME PARAMETERS

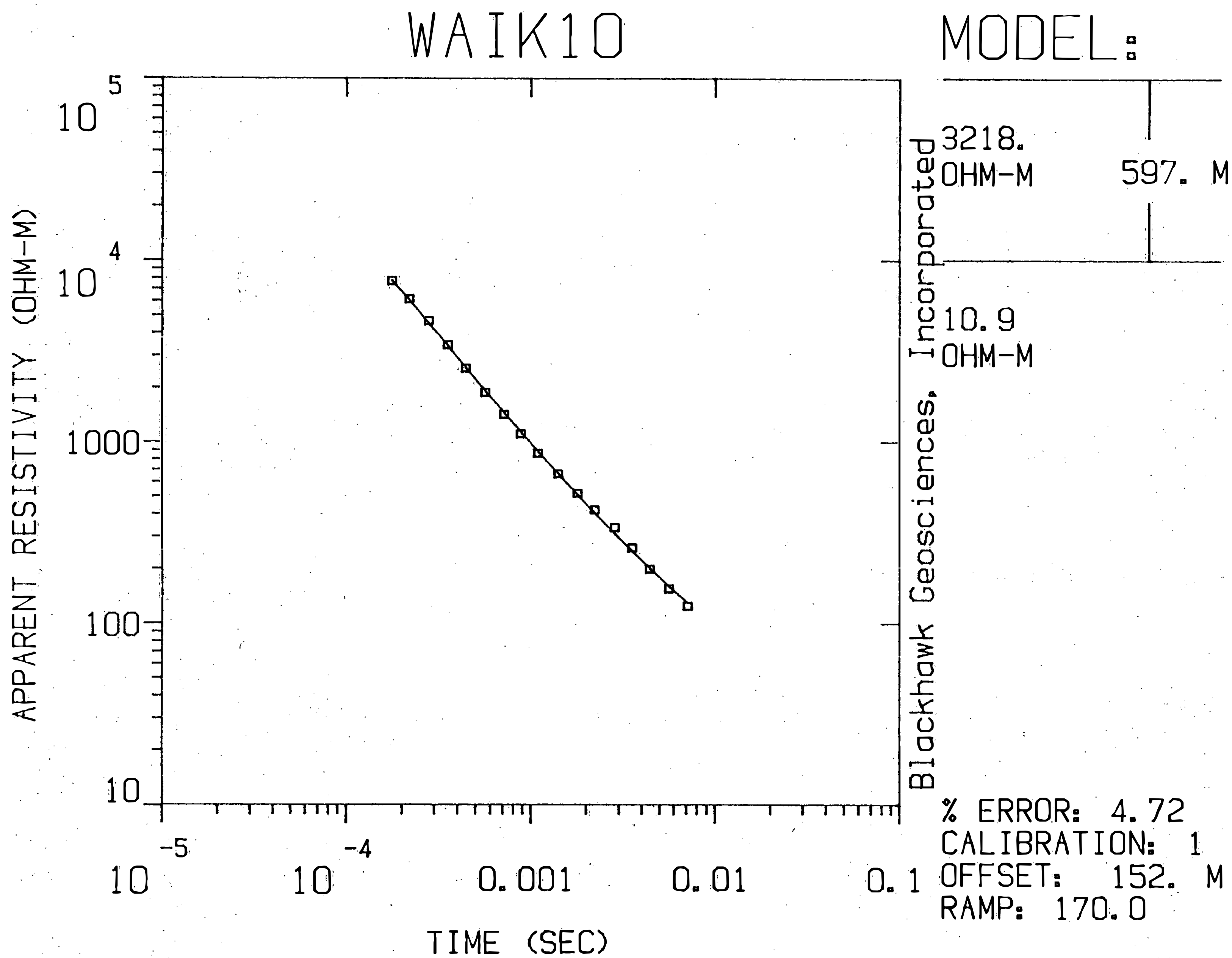
* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	1872.678	2088.394	2419.827
	2	17.218	21.791	27.162
THICK	1	645.216	655.797	666.183
DEPTH	[illegible]	[illegible]	[illegible]	[illegible]



WAIK10
MODEL:
3218.
OHM-M
597. M
10.9
OHM-M
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 4.72
CALIBRATION: 1
OFFSET: 152. M
RAMP: 170.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		426.7	1400.0		
3218.38	597.0	-170.3	-558.7	0.2	0.2
10.92					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.77E-04	7.67E+03	7.74E+03	-0.855	
2	2.20E-04	6.09E+03	6.02E+03	1.211	
3	2.80E-04	4.63E+03	4.50E+03	2.791	
4	3.55E-04	3.41E+03	3.38E+03	0.832	
5	4.43E-04	2.54E+03	2.57E+03	-1.302	
6	5.64E-04	1.87E+03	1.92E+03	-2.628	
7	7.13E-04	1.41E+03	1.45E+03	-2.771	
8	8.81E-04	1.10E+03	1.13E+03	-2.776	
9	1.10E-03	8.58E+02	8.78E+02	-2.311	
10	1.41E-03	6.59E+02	6.62E+02	-0.474	
11	1.80E-03	5.17E+02	5.07E+02	2.048	
12	2.22E-03	4.19E+02	4.03E+02	4.044	
13	2.85E-03	3.35E+02	3.11E+02	7.665	
14	3.55E-03	2.59E+02	2.49E+02	3.903	
15	4.43E-03	1.98E+02	2.01E+02	-1.490	
16	5.64E-03	1.55E+02	1.60E+02	-3.168	
17	7.13E-03	1.25E+02	1.30E+02	-4.164	

R: 152. X: 0. Y: 152. DL: 305. REC: 169. CF: 1.0000
TDHZ ARRAY, 17 DATA POINTS, RAMP: 170.0 MICROSEC, DATA: WAIK10
1103 0003 0010 Z OPR XTL L 7 10+1000
Ch.21 = 0.165 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 2.00E-02, ANTILOG YIELDS 4.7172 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.99			
P 2	0.00	0.99		
T 1	0.00	0.00	1.00	
		P 1	P 2	T 1

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	2631.285	3218.379	3202.911
	2	9.104	10.924	13.379
[illegible]	1	[illegible]	597.027	[illegible]
[illegible]	1	[illegible]	[illegible]	[illegible]